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REPORT No. R.137

THE RELATIONSHIP BETWEEN THE CREEP AND TENSILE PROPERTIES AT ELEVATED TEMPERATURE OF NIMONIC 80 - II

by

K.F.A.WALLES, B.A., and A. GRAHAM, M.Sc., D.I.C.

JUNE, 1953

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The relationship between the creep and tensile properties

at elevated temperature of Nimonic 80 - II

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K. F. A. Walles, B.A., and A. Graham, M.Sc., D.I.C.

SUMMARY

The results of a few experiments on creep recovery enable the arguments of Report No. R.100 to be extended. A new form of time-temperature variable is proposed which, without change of constants, satisfactorily co-ordinates N.P.L. and Mond-Nickel long-time creep data on Nimonic 80, N.G.T.E. short-time creep tests on Nimonic 80 drawn from store, and Mond-Nickel long-time data for an early heat of Nimonic 80A. Apart from this improvement, the situation previously reported is not affected. Support is given for the Andrade formula for creep.

CONTENTS

ILLUSTRATIONS

1.0   Relation to previous work

In previous reports (Graham 1952[1], Graham and Walles 1952[2]), a general theory of deformation which had been developed in conjunction with the results of creep and tensile tests on a commercial gas-turbine alloy is described and compared with experiment. The theory appeared to agree with experiment to within the considerable scatter of the data, some apparently systematic discrepancies being considered due either to inability, owing to the limited experimental range, to apply the theory fully, or to systematic differences between the samples of material to which the various sets of data referred. At the time it was thought that no further progress could be made without data that was either more extensive or less scattered; however, during a preliminary investigation of the possibilities of change-load and change-temperature creep tests, a new fact was discovered which enforced both a slightly modified application of the theory and a different assumption as to the influence of temperature. The changes decided upon remove the discrepancies previously found between the short-time data and various sets of long-time data, and improve and generalise the theory.

2.0   Previous work

Strong support was provided for the view that

(i)   the basis of the relation between stress σ, strain ε and time t is the Nutting equation,

$$\varepsilon = \frac{1}{\psi}\, \sigma^{\beta} t^{\kappa} , \qquad \cdots \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (1)$$

ψ, β, and κ being constants at a particular temperature,

(ii)   this relation is however to be applied incrementally so that, when the applied stress varies with time, each increment of stress contributes its own changing increment of strain; the strain is then the sum, according to the Boltzmann principle, of all the strain increments[1],

(iii)   deformation takes place by a number of modes acting concurrently, each of which makes an independent contribution to the strain in accordance with the principles (i) and (ii), the total measured strain being the sum of the contributions of all the modes.

In the ideal creep test, and approximately in many practical tests, stress is instantaneously applied to a specimen and maintained constant thereafter. All increments of stress then occur simultaneously and their Boltzmann sum for a single mode is directly expressed by (1). With several modes operative we then have

$$\varepsilon = \frac{\sigma^{\beta_1} t^{\kappa_1}}{\psi_1} + \frac{\sigma^{\beta_2} t^{\kappa_2}}{\psi_2} + \cdots \cdots \frac{\sigma^{\beta_n} t^{\kappa_n}}{\psi_n} \qquad \cdots \quad \cdots \quad (2)$$

in which ε is the total strain, the stress σ is constant for the test, and the ψ, β and κ are constants at a given temperature.

It was previously assumed that time and temperature could be combined into the single variable.

$$\theta \equiv T \left(1 - \frac{\log t}{\log t_s}\right), \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

in which $\log t_s$ is a constant; and a consequential result[2] was that κ should be proportional to absolute temperature T. In the application of (2) to a single creep curve, economy of hypothesis dictated the use of no more terms than were strictly necessary, and no justification could be found for using more than two terms each with its own freely-fitted value of κ. The secondary stage of creep was thereby taken to be merely the transition between primary and tertiary stages which were represented respectively by terms with κ averaging about 0.6 and 2.8.

The theoretical proportionality of κ to absolute temperature could not be directly detected, apparently because the small theoretical change over the range of temperature covered was of the same order as the experimental scatter; nevertheless the variable θ was very successful in co-ordinating tests at different temperatures. However, an indisputable difference was found between the values of the constant $\log t_s$ as determined from long- and short-time sets of data, and external evidence pointing to the inadequacy of (3) was discovered later.

3.0   New evidence on form of creep curve

A prediction of the theory of Reference 1 is that, after unloading a creep specimen, complete recovery should eventually take place of the strain contributed by any mode with κ less than 1. In conjunction with the representation of a creep curve up to the apparent onset of accelerating creep by a single term with κ about 0.6, this implied that all the non-accelerating strain should be recoverable. However, when certain difficulties with the change-load and change-temperature creep tests previously mentioned led to a few tests of recovery, the results shown in the self-explanatory Figures 1 and 2 were obtained; and it is quite evident from these that the amount of strain recovered is often much smaller than the non-accelerating strain. Where the latter is divisible into marked "primary" and "secondary" stages, the recovered strain appears more nearly equal to the primary strain; hence the assumption that all the non-accelerating strain is due to a single term in (2) must in general be abandoned.

With such direct experimental support for the conventional splitting of the creep curve into decelerating, steady state, and accelerating stages, the Andrade equation, which may be written

$$\varepsilon - \varepsilon_0 = pt^{\frac{1}{3}} + qt, \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

the terms of which correspond broadly to primary and secondary stages, deserves special attention. In this, ε_0, p and q are constants for a particular test. It will be noted that

(a)   (4) is a special case of (2),

(b)   Andrade and his collaborators have provided consider-able experimental support for his equation for a variety of materials[3],

(c)   the non-accelerating portions of the creep curves
       of Figures 1 and 2 are well fitted by (4) with
       $\varepsilon_0 = 0$,

(d)   according to the present theory, only the strain
       due to the term $\beta t^{\frac{1}{3}}$ on the right should be
       recoverable, and, in agreement with this, the
       amount of strain recovered in Figures 1 and 2 is
       about equal to the contribution from this term.

The Andrade equation does not include accelerating creep, and the
inclusion of another term in accordance with (2) was therefore necessary.
It was found on re-analysis of the data that the fit of the two terms on
the right of (4) to the decelerating portions of the creep curves was
practically indistinguishable from that of the previous single term, and
that the accelerating strain that remained to be accounted for was substan-
tially the same whether one or two terms was used. Now, if the exponents
of the first two terms are in fact the rational quantities $\frac{1}{3}$ and 1, it is
rather unlikely that the exponent of the third term will be an irrational
number circa 2.8 as previously found: this number is thus probably an
approximation to 3. It was found by trial that, with the predetermined
values $\frac{1}{3}$, 1 and 3, the whole set of creep curves could be fitted at least
as well as with previous two terms with freely-adjustable exponents: and
the new assumption was therefore considered justified. The change has the
additional advantage of requiring one less adjustable constant to be
determined from a creep curve.

4.0   New form of time-temperature variable

An immediate consequence of these developments was that the theoreti-
cal assumption concerning the influence of temperature could not be accepted.
For the success of the Andrade equation with its fixed exponents in applica-
tion to a wide range of materials tested at temperatures that are different
fractions of their melting-points suggested that the exponents of time are
not temperature dependent, and hence that the time-temperature variable (3),
which requires an exponent proportional to temperature, should be rejected.
Analysis of the data in accordance with the new fixed exponents showed that
a suitable form for a new time-temperature variable ϕ would be (see Appendix)

$$\log \phi = \log t + f(T' - T), \qquad \cdots \quad \cdots \quad \cdots \quad (5)$$

where T' is a constant; but the data could not establish the form of the
function f, for more than one choice could be made whereby, when all the
available data were analysed together, the overall fit was better than
could be obtained with (3).

For theoretical reasons that have been partly given and will be set
out more fully in a later report - they are concerned with the wider-range
requirements of a deformation theory - the suggestion of Nutting was accepted
that temperature should appear in equation (1) symmetrically with the other
variables thus:

$$\varepsilon = C \, \sigma^\beta t^\kappa T^\nu , \qquad \cdots \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (6)$$

in which ν and C are new constants and all exponents are now independent of
temperature. For reasons similar to those given in Reference 1, such an

equation should be applied incrementally; and then, on the assumption that the incremental changes in respect of temperature are to be summed in the Boltzmann manner from some temperature T' (which may for example be related to a particular temperature in the history of manufacture of the material), the summation for creep conditions and a single deformation mode leads to the form

$$\varepsilon = C\ \sigma^{\beta}t^{\kappa}\ (T' - T)^{\nu}, \qquad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (7)$$

in which C, β, κ, T' and ν are the constants appropriate to the mode. The corresponding form of the relation between time and temperature for fixed stress and strain is therefore

$$t\ (T' - T)^{\nu/\kappa} = \text{constant}, \qquad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (8)$$

and thus the desired form of equation 6 becomes

$$\left. \begin{array}{l} \log \phi = \log t - A \log (T' - T) \\ \phi = t\ (T' - T)^{-A}, \end{array} \right\} \qquad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (9)$$

in which $A \equiv -\nu/\kappa$. This now replaces (3). Equation 7 may now be written

$$\varepsilon = C\ \sigma^{\beta}\phi^{\kappa} \qquad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (7a)$$

5.0 New form of creep equation

It was found that (9) was experimentally acceptable, for it would correlate the long- and short-time sets of data with a single choice of the values of A and T'. When temperature is thus incorporated, equation 2 is replaced by

$$\varepsilon = C_1\sigma^{\beta_1}t^{\kappa_1}\ (T'_1 - T)^{\nu_1} + C_2\sigma^{\beta_2}t^{\kappa_2}\ (T'_2 - T)^{\nu_2} + \dots$$

or   (10)

$$\varepsilon = C_1\ \sigma^{\beta_1}\phi_1^{\kappa_1} + C_2\sigma^{\beta_2}\phi_2^{\kappa_2} + \dots ,$$

each term, having, in principle, its own values of the constants.

With attention limited to a single creep curve, only three terms of equation (10), having time exponents $\frac{1}{3}$, 1 and 3, could be distinguished. However, when, for the family of curves, each of these terms was separately cross-plotted in the form $\log \sigma$ versus $\log t$ at constant strain and temperature, it was found that the term with time-exponent 3 plotted not as a single straight line (see below) but as two straight lines meeting in a fairly sharp transition. The simplest explanation of this result in terms of the theory,

following the lines of the previous report, was that equation 10 for the present material contained two terms with the same time exponent $\kappa = 3$, although with different values of β and C. Experiment gave no clear indication of a difference between the values of A and T' in the different terms (see Section 8.0), and the form of (10) finally adopted was therefore, in view of (9),

$$\varepsilon = C_1\sigma^{\beta_1}\phi^{\frac{1}{3}} + C_2\sigma^{\beta_2}\phi^1 + (C_3\sigma^{\beta_3} + C_4\sigma^{\beta_4})\phi^3 \quad .. \quad .. \quad (11)$$

6.0   Method of reduction of creep data

A detailed account of the method of reduction in terms of the foregoing theory is given in Reference 4 from which the self-explanatory Figure 3 is taken. Briefly it proceeds by resolving each creep curve individually into its $t^{\frac{1}{3}}$, t^1 and t^3 components of strain, and then, for each of these components separately, and considering all curves together, determining the constants in the terms of (10) by use of the foregoing equations.

It is sufficient for present purposes to notice that, if t^* is the time when any term of (10) has unit value, then, for that term,

$$C\sigma^\beta t^{*\kappa}(T' - T)^\nu = 1,$$

or

$$\log C + \beta \log \sigma = - \kappa \log t^* - \nu \log (T' - T) \quad .. \quad .. \quad .. \quad .. \quad .. \quad (12)$$

which shows that the log σ versus log t^* plot for a single term at any constant temperature should be a straight line. Also, at any fixed stress, if the term considered reaches unit value in time t_1^* at temperature T_1 and time t_2^* at temperature T_2, (12) shows that

$$\log C + \beta \log \sigma = - \kappa \log t_1^* - \nu \log (T' - T_1^*)$$

$$= - \kappa \log t_2^* - \nu \log (T' - T_2), \quad .. \quad .. \quad .. \quad .. \quad (13)$$

so that, with $- \nu/\kappa = A$, and

$$\log t_1^* - \log t_2^* \equiv \Delta \log t$$

(the displacement along the log t axis between the lines for T_1 and T_2), we find

$$\Delta \log t = A \left\{ \log (T' - T_1) - \log (T' - T_2) \right\} \quad .. \quad .. \quad .. \quad (14)$$

which is independent of stress.

With A and T' determined by use of (14), time and temperature may be combined <u>in the term considered</u> in a variable ϕ^*; for (12) with (9) may be written

$$\log C + \beta \log \sigma = - \kappa \log \phi^* \quad .. \quad .. \quad .. \quad (15)$$

in which ϕ^* is the value of the time-temperature variable for which the strain <u>contributed by the term</u> has unit value.

7.0   Data analysed

The N.P.L. and N.G.T.E. sets of creep data previously studied were re-analysed in terms of the foregoing theory together with a long-time set kindly offered to us by the Mond Nickel Company as probably being more representative of the heats used in the N.G.T.E. experiments than their standard tabulated data for Nimonic 80 with which comparison was previously made.   The data related to

(a)   an early heat of Nimonic 80 tested by the N.P.L. at temperatures of 600°C., 650°C. and 700°C. for times up to 1,300 hours,

(b)   later heats of Nimonic 90 used by N.G.T.E. for short-time tests at 700°C., 750°C., 800°C. and 850°C., the longest test being of 200 hours duration, while the majority were completed in 24 hours,

(c)   an early heat (Z88) of Nimonic 80A, tested by the Mond Nickel Company at temperatures of 650°C., 700°C. and 750°C. for times up to 22,000 hours.

A limited further comparison has also been made with the tabulated Nimonic 80 data, such tabulated data being insufficient for full analysis.

Attention was confined to strains below 1 per cent.   The raw data is too extensive for presentation, but since it was found that the extended Andrade equation fitted the creep curves, except at strains near to fracture where cracking may have occurred, in almost every case to within the local irregularities of the experimental points, the derived Figures 4 to 6 represent the data very closely.   The scatter of the points is mainly due to variability of the material, and, since the values of κ are now pre-determined, the individual creep curves may be closely reconstructed from the points that are given.

8.0   Values of A and T'

The above three sets of data were separately analysed, and values of $\Delta \log t$ were derived from the best straight lines drawn through the plots of $\log \sigma$ versus $\log t^*$ at constant temperature (equation 12); the scatter of the points was however such that owing to the comparatively small range of temperature covered by each set, reliable values of T' could not be obtained from any one set of data considered in isolation.   The difficulty of determining these constants by creep tests of the usual kind is that, in principle, behaviour at different temperatures and therefore of different specimens must be compared, so that uncertainty introduced by variations of the material is at a maximum.   Accordingly, and in view of the indications of tentative

analyses, the data for all the materials was treated as a single set for the purpose of obtaining $\Delta \log t$. This implied that the materials all had the same values of A and T', an assumption found later to be justified by its full co-ordination of the data. The best values of $\Delta \log t$ for calculation of these constants were taken to be the average of the values from all three sets.

Table I (a) - (c), in which $\Delta \log t$ relates to the 50°C. interval between the two temperatures at the head of each column, gives values for the $t^{\frac{1}{3}}$, t^1, and t^3 components respectively of the creep curves.

Experimental results for the t^3 term showed less scatter than for the other two terms, the scatter in this term being small enough for the marked increase shown in Table I(c) of $\Delta \log t$ with temperature to be beyond dispute. Since use of the previous time-temperature variable θ (equation 3) can only give a decrease of this quantity with temperature (see Appendix), the result shows rather conclusively that θ is unacceptable.

Reasons for the choice of ϕ defined by (9) are given in para. 2 and in the Appendix. Use of this quantity with A = 22.5, T' = 1175°C. was found to give values of $\Delta \log t$ which fitted the data for the t^3 term to within the scatter.

The values in Table I(a) for the $t^{\frac{1}{3}}$ term suggest a trend of $\Delta \log t$ with temperature in the opposite direction, namely a decrease, but the evidence is unreliable, for the strain concerned was near to the sensitivity-limit of the extensometers used in some of the experiments, and loading conditions may also have had some effect. The three entries for material (b) in particular are uncertain. The t^1 term, which for this material appears to contribute little to the total strain, is in many but not all experiments rather poorly defined experimentally. Since the well defined values of A and T' for the t^3 term were found to suit both the $t^{\frac{1}{3}}$ and t^1 data to within the considerable scatter, they were adopted for all the terms in the absence of justification for introducing additional constants. The values of $\Delta \log t$ calculated from the chosen values of the constants are shown in the table for comparison with the experimental values.

9.0   Co-ordination of long- and short-time data

With A and T' established for each of the terms in (10), the data for each may be plotted separately against ϕ^* in accordance with (15), ϕ^* being the value of ϕ (equation 9) for which the particular term of (10), now reduced to (11), has unit value. The result on the form $\log \sigma$ versus $\log \phi^*$ is given in Figures 4, 5, and 6, in which, as the legends show, points derived from different sources are distinguished by their shapes while the temperatures of testing are indicated by tags. The curves are a superposition of the separate $\log \sigma / \log t^*$ curves (not shown) by displacement along the log t axis, and therefore directly include the scatter due to variability of the material, increased perhaps by systematic effects resulting from an experimental error in A and T'; however such effects are not reliably discernable; they are certainly small for the t^3 - now ϕ^3 - term which is the most important.

If attention is confined for the present to stresses above 8 t.s.i. (log σ above 0.9), it will be seen first of all that, when each set of data is considered in isolation, results for different temperatures and therefore different times to reach the unit strain are co-ordinated by the common time-temperature variable to within the scatter; for distances of individual

points from the best straight line drawn through any set do not vary systematically with temperature and are of the same order as the separation between points for repeat experiments.

For each set separately, the points for the $t^{\frac{1}{3}}$ and t^1 terms lie to within the scatter of the material upon single straight lines as required (c.f. 12). For the t^3 term in (11) Figure 6 shows points lying upon two straight lines in accordance with the double nature of this term.

So far there is little to choose between ϕ and the previously used θ, but the particular virtues of ϕ are at once shown when the different sets of data are compared. For the common values of A and T' are now equally suitable for all three sets of data; moreover, the slopes of the straight lines drawn through the sets closely agree, so that, since these slopes are κ/β (c.f. (15)), and the fixed κ are common to all sets, the constants β are also shown to be common to the several sets. In other words, from the present viewpoint, the series of materials that has resulted from a continuous improvement of the alloy from an early stage of development differ from each other only in a steadily increasing trend of the constants C, the later materials being the stronger. The data for the different materials, which are thus satisfactorily co-ordinated, covers a time range of 10^+ to 1.

An important result of the previous work was that the discontinuities in the plots of log σ versus θ occurred in the N.G.T.E. experiments and Mond Nickel tabulated data at substantially the same values of log σ and θ. The latter data is insufficient for analysis into terms, and consideration of it is deferred until Section 10.0; however, a similar transition is found in Figure 6 in the Mond Z88 data (c). As before, the N.P.L. data do not extend sufficiently into the low-stress region to reach the transition. The transition was previously most clearly marked at the higher strains, and in the present analysis it is now seen to be confined to the ϕ^3 term. Figure 6 shows that there is again very close agreement between N.G.T.E. and Mond data, thus confirming the important point that this transition of the type normally attributed to a metallurgical change, is governed by substantially the same time-temperature relationship as the mechanical variables stress and strain. The above results as a whole are fully consistent with the view that A, T' and β are the same for all the materials, and the implication that C differs between them is directly confirmed by a comparison between points for different materials tested at the same temperature and stress. Some points of this kind are indicated in Figures 4 to 6 to facilitate comparisons.

At stresses below 8 t.s.i. the points derived from the long-time set (c) data do not fit well; but the original data, especially at small strains, show inconsistencies which, while probably not affecting the validity of the ordinary stress/log time or log stress/log time plots for a given temperature, give rise to difficulty when the variation with temperature is considered.

At these lower stresses (longer times, higher temperatures), there is a marked tendency for points to fall below the line drawn through points for higher stresses, and not to be co-ordinated by the constants that have been chosen for the time-temperature variable. This may indicate the presence of another mode with different constants A and T', but there is too little evidence to establish the possibility.

10.0 Discussion and summary

As with the previous time-temperature variable θ, use of ϕ does not necessarily require application of the remainder of the theory; for the present data are satisfactorily co-ordinated by the principle that time and temperature occur only in the combination

$$t\,(1175 - T)^{22.5} \equiv \phi_1 \qquad (T \text{ in } {}^{\circ}C.) \quad .. \quad .. \quad .. \quad (16)$$

Although, in order to arrive at this result, the separate parts of the creep curves were analysed separately, this complication has been shown, for the present material and for the purpose of this particular relationship, to be not strictly necessary, since all terms are co-ordinated to within the scatter by using the common constants in ϕ as given in (16). In Figures 7 and 8, $\log \sigma$ is plotted for various constant total strains against $\log \phi_1{}^*$, in which $\phi_1{}^*$ is the value of ϕ_1 in (16) when t is such that the total creep strain in the experiment considered has the values 0.05 per cent, 0.1 per cent, 0.2 per cent, 0.5 per cent. For these circumstances, tabular data may readily be included, and points for Nimonic 80 taken from the Mond Nickel booklet[5] are accordingly shown. The graphs are consistent with a progressive development of the material. It will be noted that constancy of the total strain does not involve constancy of the $t^{\frac{1}{3}}$, t^1, and t^3, constituents of a creep curve (Figures 4-6 are each for a constant strain contribution of the term). Thus if the lines in Figures 4-6 were straight, those in Figures 7 and 8 would not in general be so, and conversely. Nevertheless, for the present material, the difference for the two methods of plotting is hardly distinguishable within the scatter. The impression left by a detailed study of the results is that cross-plotting for constant total strain is approximate and cross-plotting for constant strain in a particular term is to be preferred, but further work is necessary to establish the point.

The possibility of predicting long-time results from short-time experiments is clearly demonstrated by the Figures; the practicability of doing so, however, depends both upon the time and effort required to establish the two constants in ϕ and upon whether, for other materials, the corresponding constants are effectively the same for all parts of the range. These are problems upon which further work is being planned.

The values of the constants found for the material in its different stages of development are given in Table II, and the theoretical lines appropriate to these values are indicated in Figures 7 and 8. The lines drawn are those for the short-time N.G.T.E. results shown as filled-in circles, and these are representative of those for the other sets of points.

From the constants given, the original creep curves can be reconstructed to within an error corresponding to the scatter of the points which is largely random. If it should be thought that the number of freely-adjustable constants used in attaining this agreement is excessive, one should reflect upon the minimum number that might be expected successfully to represent the creep of a complex alloy each of whose constituents is no doubt able to deform in a variety of ways. The constants apparently arise from four important modes of deformation, all similar in that they are expressed by formulae of the same type with some common constants, but different in that some of the constants are different. Direct evidence for independent modes was provided by the N.P.L. creep data as discussed in Section 4.0 of Reference 1 and by the recovery experiments described in

Section 3.0 of the present report. However, it is a problem for the future to reduce the number of constants and to establish their values by independent means. The regular sequence $\frac{1}{3}$, 1, 3, of values of κ engenders the hope that similarly simple relationships may occur elsewhere, and some significance may be found in the fact that the value established for T', namely 1175°C. is close to the rolling temperature of 1200°C. used for the material.

The relationships previously predicted[1] and verified experimentally[2] between the results of creep tests and two forms of tension test are substantially unaffected by the improvements made to the theory in the present report; and to these successes is now added the experimentally-verified prediction that the strain associated with the primary portion of the present creep curves is recoverable. There is now therefore firm evidence for a commercial material for the validity of the superposition or memory-principle in the form in which it has been introduced into the theory. The particular combination of this principle with the Nutting equation which leads to (1) for creep conditions, and the further assumption of independent modes of deformation which leads to (2), is fully confirmed to within the scatter of the data. This is rather large, however, and it appears unlikely that final conclusions will be reached on the basis of simple creep tests alone.

This point is of sufficient importance to be emphasised, and the following resumé of the steps in the argument provides the key to progress in the future. For it was not creep tests alone, but the comparison of creep with tensile-test results which showed up in Reference 1 the deficiencies of a simple equation of state and of the simple Nutting equation; also the same comparison was needed to show that the deformation modes operated concurrently rather than in succession. Similarly the need for a 3-term Andrade-type expression for a creep curve is but weakly defined by creep tests, but was immediately made evident for the present curves when creep and recovery results were compared. Again, a single set of creep data of the ordinary kind, even with a few long-time results, was not sufficient directly to decide the form of a time-temperature relationship; but the relationship became much more closely defined when data covering a temperature range of 250°C. was considered in the light of more general requirements. Owing to the apparent complexity of the phenomena, it is only from widely dispersed sources that firm conclusions may be drawn, and in an attempt to cover a wide range of the variables, a collaborative research with other investigators on a common material is being arranged. Consideration is also being given to providing results for other forms of test than simple creep tests.

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TABLE I

Values of $\Delta \log t$

Term	Temperature of testing °C. T_1 / T_2	600 650	650 700	700 750	750 800	800 850
(a) $t^{\frac{1}{3}}$	$\Delta \log t$ material (a)*	1.08	0.86			
	material (b)*			0.48	0.92	0.72
	material (c)*		0.99	0.39		
	mean values	1.08	0.92	0.44	0.92	0.72
(b) t^{1}	$\Delta \log t$ material (a)	1.31	1.25			
	material (b)			1.20	1.10	1.66
	material (c)		1.09	1.05		
	mean values	1.31	1.17	1.12	1.10	1.66
(c) t^{3}	$\Delta \log t$ material (a)	0.95	0.92			
	material (b)			1.00	1.18	1.43
	material (c)		1.06	0.94		
	mean values	0.95	0.99	0.97	1.18	1.43
Calculated values of $\Delta \log T$	From equation (3)[+]					
	$\log t_s = -17.3$	1.17	1.11	1.06	1.00	0.96
	$\log t_s = -24.8$	1.59	1.51	1.43	1.36	1.30
	From equation (9)					
	$A = 22.5$, $T' = 1175$°C.	0.89	0.98	1.08	1.22	1.40

*See Section 7.0

[+]Taking a mean time of 100 hours

TABLE II

Constants derived from the analysis

for the three materials

All terms, A = 22.5, T' = 1175°C.

Constant		$t^{\frac{1}{3}}$ term	t^1 term	t^3 term (i)	t^3 term (ii)
All materials	κ	$\frac{1}{3}$	1	3	3
	β	2.42	5.85	22.1	13.9
	κ/β	0.137	0.171	0.136	0.216
log C – material (a)		16.54	50.77	146.82	–
log C – material (b)		16.14	50.53	145.03	154.74
log C – material (c)		16.19	49.63	143.88	154.14

APPENDIX

Reasons for choice of time-temperature variable ϕ

The discussion of paragraph 3 shows that change of the exponent κ with temperature is improbable, while no evidence has been found that β varies with temperature - indeed, if one of the terms of (2) represents elastic strain, the corresponding β is necessarily unity at every temperature - and it is therefore probable that ψ alone is temperature-dependent, that is, $\psi \equiv \psi$ (T).

The factors of (2) containing time and temperature are then t^{κ}/ψ (T) $\equiv \phi^{\kappa}$, where ϕ is the time temperature variable, or in the logarithmic form

$$\log \phi = \log t + f\ (T) \quad .. \quad .. \quad .. \quad .. \quad (a)$$

where
$$f\ (T) = \frac{1}{\kappa} \log \psi\ (T)$$

The experimental values in Table I show that $\Delta \log t$ is negative, (since shorter times correspond to higher temperatures), and, for the t^3 term at least, that its magnitude increases with temperature. An acceptable form of ϕ must therefore make both $\left(\dfrac{\partial \log t}{\partial T}\right)_{\phi}$ and $\left(\dfrac{\partial^2 \log t}{\partial T^2}\right)_{\phi}$ negative.

These quantities are given in Table A below for several conceivable forms of time-temperature variable, all of which have been chosen to give negative values of $\left(\dfrac{\partial \log t}{\partial T}\right)_{\phi}$.

It is seen that forms (i)-(iii) give positive values of $\left(\dfrac{\partial^2 \log t}{\partial T^2}\right)$, and cannot fit the results of Table I: thus both the previous variable θ and the form (ii) derived from the classical temperature factor $t\ell \frac{Q}{RT}$ are ruled out.

The value given by (iv) is zero, which is still unsatisfactory, while (v), although giving the required sign, has a fixed relation between $\left(\dfrac{\partial \log t}{\partial T}\right)$ and $\left(\dfrac{\partial^2 \log t}{\partial T^2}\right)$ (see fourth column of A) which does not satisfactorily fit the results of Table I. The form (vi) with variable exponent n of temperature is satisfactory in that both the magnitude and rate of change of $\Delta \log t$ are adjustable: but since two constants are required to attain this result, it appears preferable to introduce the additional constant as a fixed temperature T' from which T is to be measured rather than as in (vi) as an adjustable exponent; for it seems probable that the temperature of melting or of metallurgical changes that may occur in manufacture are particularly relevant to creep. Thus equation (a) is written in the form

$$\log \phi = \log t + f\ (T' - T) \quad .. \quad .. \quad .. \quad .. \quad (b)$$

which is equation (5) in the report. Either of the modified forms (ii)' and
(iii)' of f (T' - T) now satisfy the necessary conditions, as seen in
Table A, provided T' is greater than T; and the choice between these and
other possible forms is made on the broad theoretical grounds indicated in
Section 4.0. Some support for the chosen form (iii)', rather than (ii)' is
however provided by the fact that the value of T' appropriate to (iii)' is
found to be 1175°C., a temperature within the manufacturing range, while
(ii)' requires a value above the melting point of the alloy.
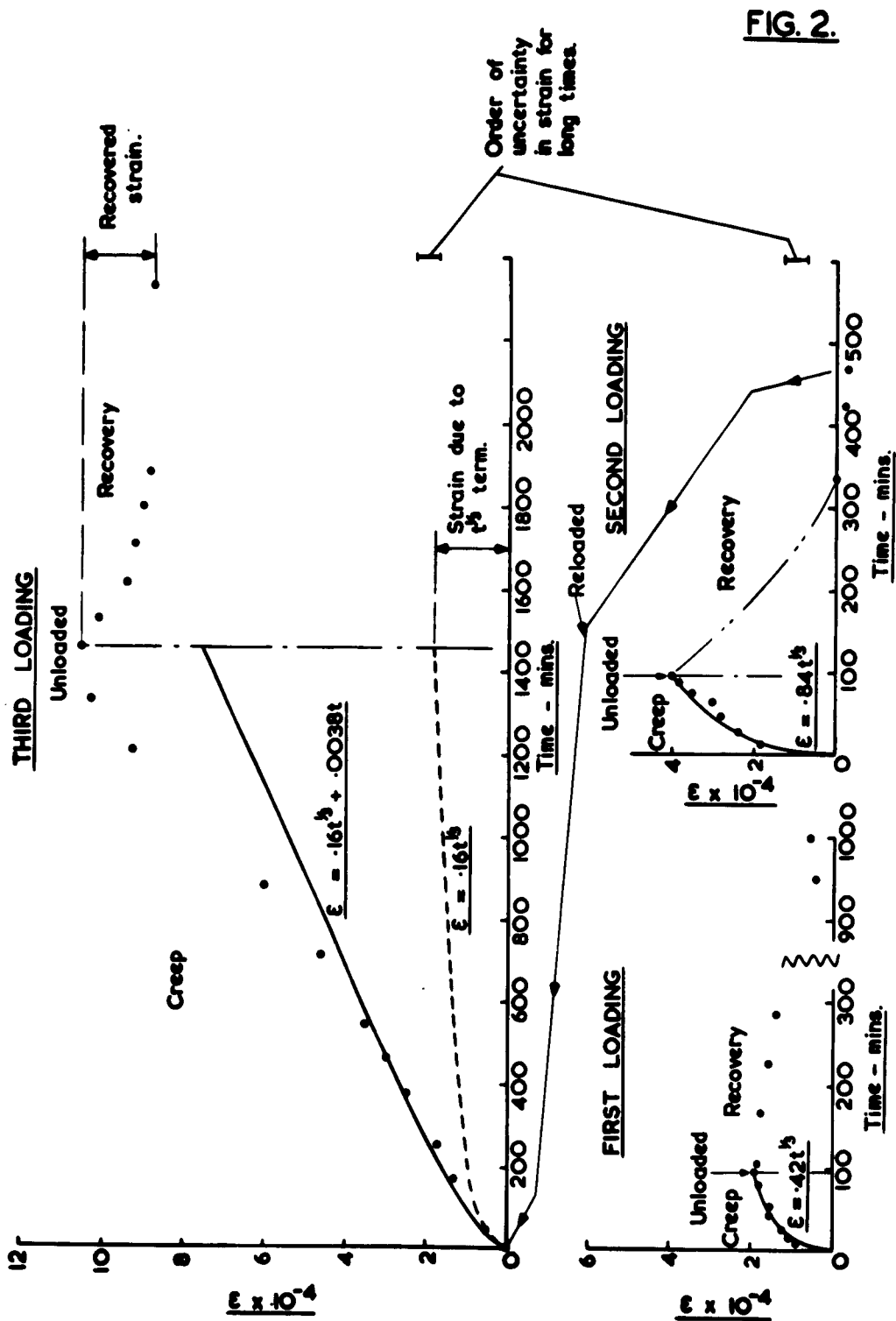
TABLE A

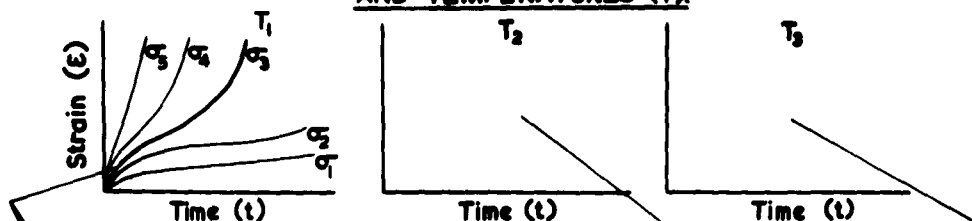| Time-temperature variable	$\left(\dfrac{\partial \log t}{\partial T}\right)_{\phi}$: sign	$\left(\dfrac{\partial^2 \log t}{\partial T^2}\right)_{\phi}$: sign	$\left(\dfrac{\partial^2 \log t}{\partial T^2}\right)\Big/\left(\dfrac{\partial \log t}{\partial T}\right)$
(i) $\theta = T - T'\dfrac{\log t}{\log t_s}$	$\dfrac{\log t_s - \log t}{T}$:-	$-\dfrac{\log t_s - \log t}{T^2}$:+	$-\dfrac{1}{T}$
(ii) $\log \phi = \log t - \dfrac{C}{T}$	$-\dfrac{C}{T^2}$:-	$+\dfrac{2C}{T^3}$:+	$-\dfrac{2}{T}$
(iii) $\log \phi = \log t + \mathcal{A} \log T$	$-\dfrac{\mathcal{A}}{T}$:-	$\dfrac{\mathcal{A}}{T^2}$:+	$-\dfrac{1}{T}$
(iv) $\log \phi = \log t + BT$	- B :-	0	0
(v) $\log \phi = \log t + DT^2$	- 2DT :-	- 2D :-	$\dfrac{1}{T}$
(vi) $\log \phi = \log t + ET^n$	$- nET^{(n-1)}$:-	$-n(n-1)ET^{(n-2)}$:-	$\dfrac{n-1}{T}$
(ii)' $\log \phi = \log t + \dfrac{C}{T' - T}$	$-\dfrac{C}{(T' - T)^2}$:-	$-\dfrac{2C}{(T' - T)^3}$:-	$\dfrac{2}{T' - T}$
(iii)' $\log \phi = \log t - \mathcal{A} \log (T' - T)$	$-\dfrac{\mathcal{A}}{T' - T}$:-	$-\dfrac{\mathcal{A}}{(T' - T)^2}$:-	$\dfrac{1}{T' - T}$

SK 6585

FIG. 1.
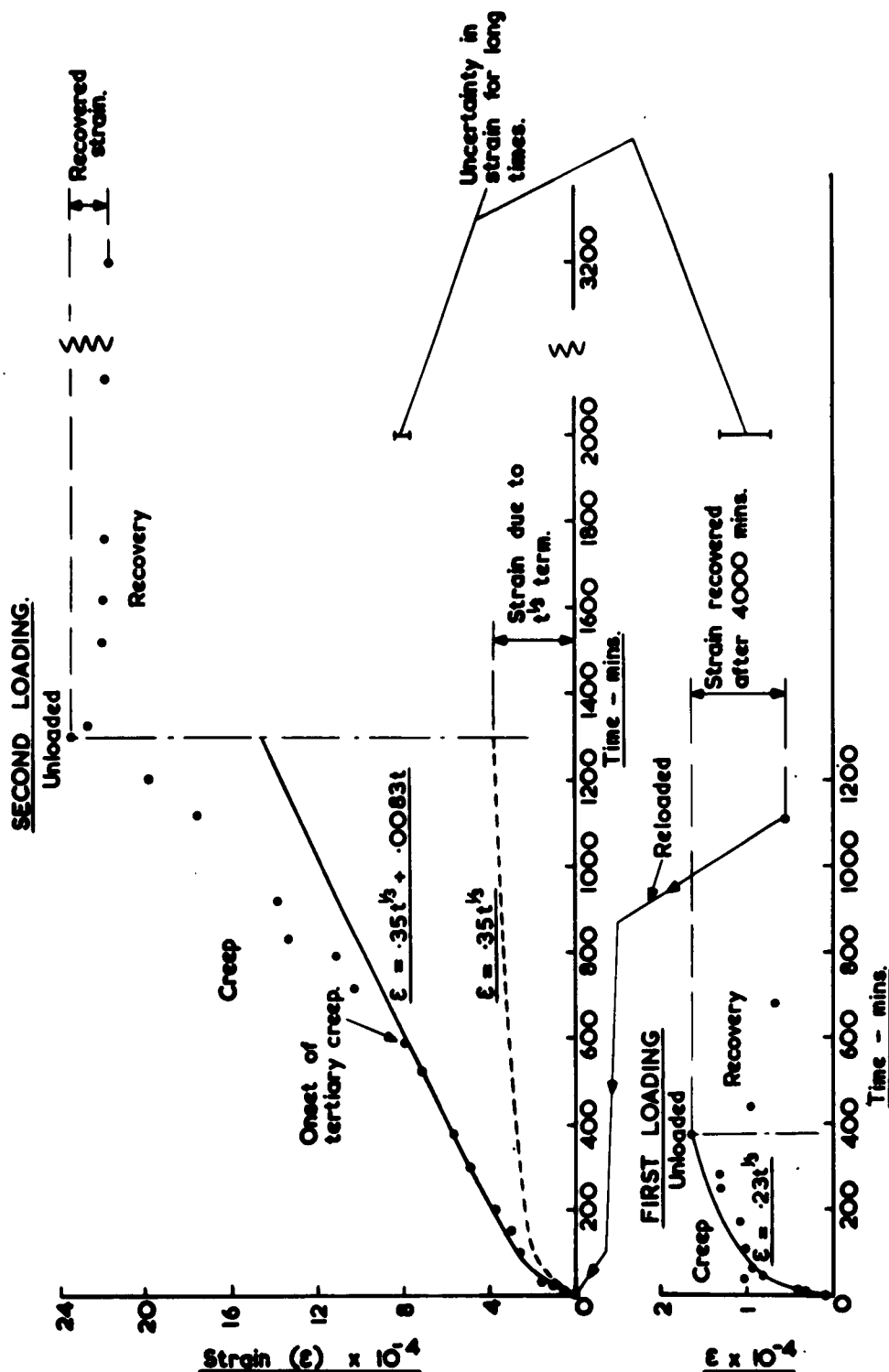
STRAIN - TIME RESULTS FOR RECOVERY TESTS.
FIRST SPECIMEN.

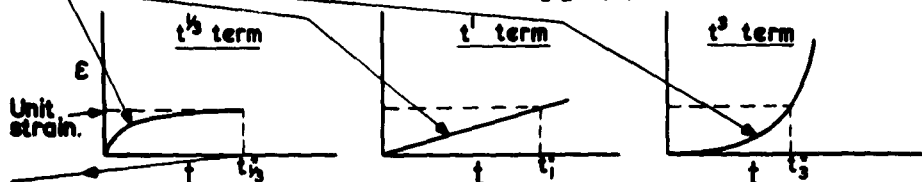# FIG. 2.

STRAIN - TIME RESULTS FOR RECOVERY TESTS.
SECOND SPECIMEN.

FIG. 3.

SK 6587

**(a) EXPERIMENTAL CREEP CURVES FOR VARIOUS STRESSES (σ) AND TEMPERATURES (T).**

Strain (ε)

T_1 σ_5 σ_4 σ_3 σ_2 σ_1

T_2 T_3

Time (t)   Time (t)   Time (t)

(b) ANALYSIS OF CREEP CURVE WITH STRESS σ_5, TEMPERATURE T_1 INTO TERMS $\varepsilon = \left[\dfrac{t}{t_{\frac{1}{3}}}\right]^{\frac{1}{3}} + \left[\dfrac{t}{t_1}\right]^{1} + \left[\dfrac{t}{t_3}\right]^{3}$

ε

$t^{\frac{1}{3}}$ term t^{1} term t^{3} term
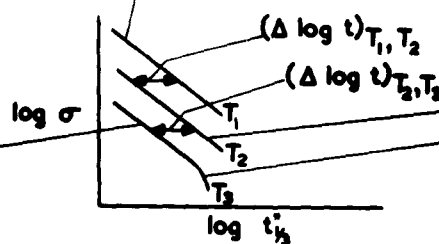
Unit strain.

t $t_{\frac{1}{3}}$ t t_1 t t_3

Other creep curves similarly analysed.

(c) CROSS-PLOTTING OF LOG STRESS vs LOG TIME, AT CONSTANT TEMPERATURE, FOR UNIT STRAIN IN $t^{\frac{1}{3}}$ TERM.
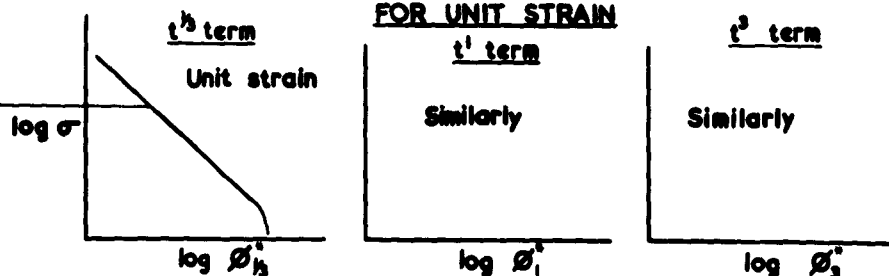
σ_1 σ_2 σ_3 σ_4 σ_5 T_1

$\log \sigma$

$\log t_{\frac{1}{3}}$
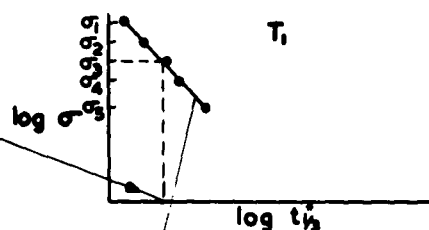
similarly

(d) CROSS-PLOTTING FOR EACH TEMPERATURE OF TESTING — DETERMINATION OF $\Delta \log t$.

$(\Delta \log t)_{T_1, T_2}$

$(\Delta \log t)_{T_2, T_3}$

$\log \sigma$

T_1

T_2

T_3

$\log t'_{\frac{1}{3}}$

(e) CROSS-PLOTTING OF ALL RESULTS AS LOG σ vs LOG ϕ FOR UNIT STRAIN

$t^{\frac{1}{3}}$ term t^{1} term t^{3} term

Unit strain   Similarly   Similarly

$\log \sigma$

$\log \phi''_{\frac{1}{3}}$ $\log \phi''_1$ $\log \phi''_3$

METHOD OF REDUCTION OF CREEP DATA.

FIG. 4.

$\varepsilon = 0.1\%$

Discrepancy scale.

Relative stress levels (at fixed ϕ)

Repeat tests.

Examples of direct comparisons.

(a) with (c)

(a) with (c)

(b) with (c)

(b) with (c)

Material (a) N.P.L. long-time tests.
Material (b) N.G.T.E. short-time tests.
Material (c) MOND long-time tests.

600°C.
650°C.
700°C.
750°C.
800°C.
850°C.

$60 + \log \phi$

$\log \sigma$

LOG σ VERSUS LOG ϕ FOR $t^{\frac{1}{2}}$ TERM.

FIG. 5.

SK 6589

LOG σ VERSUS LOG ø FOR t' TERM.

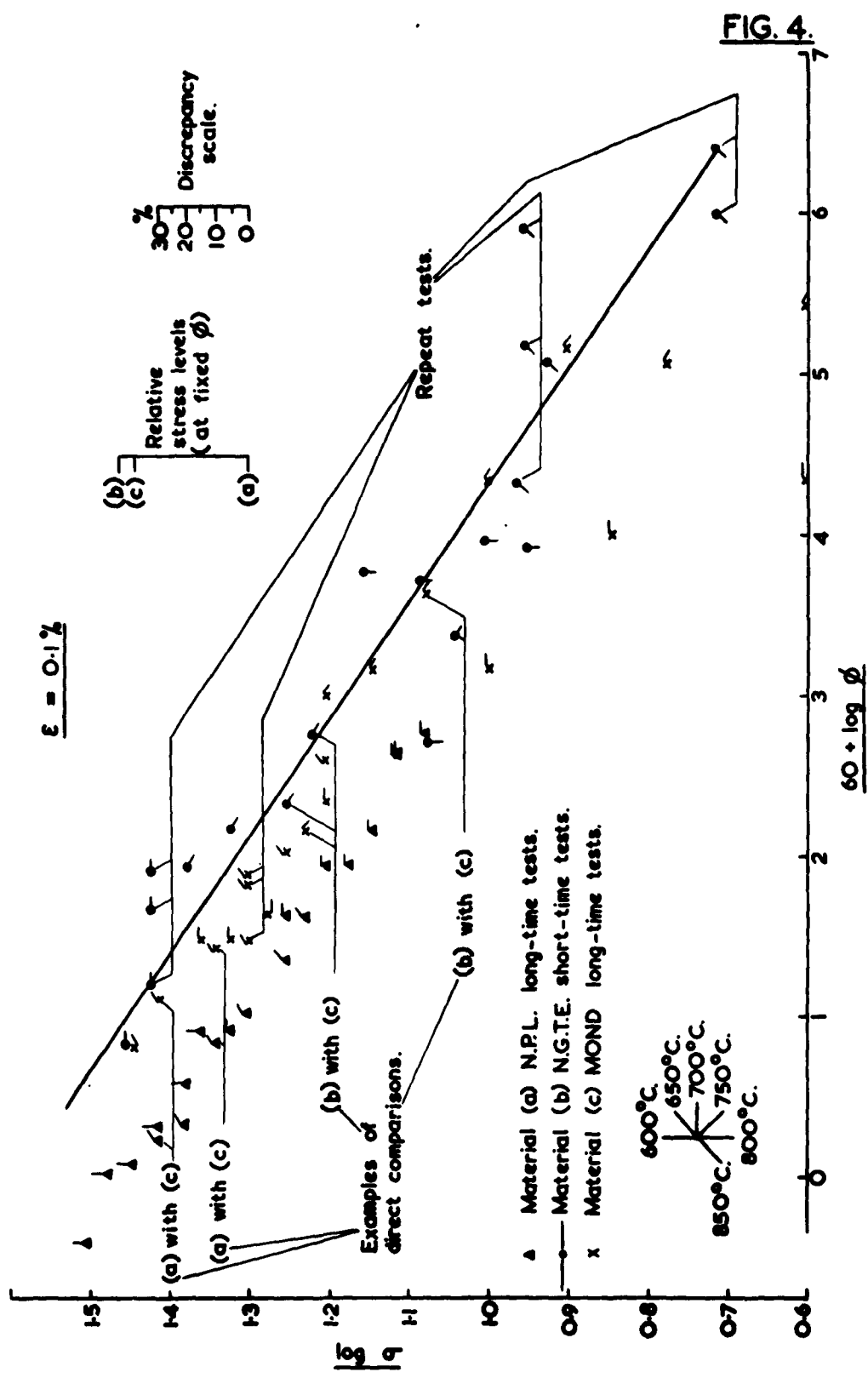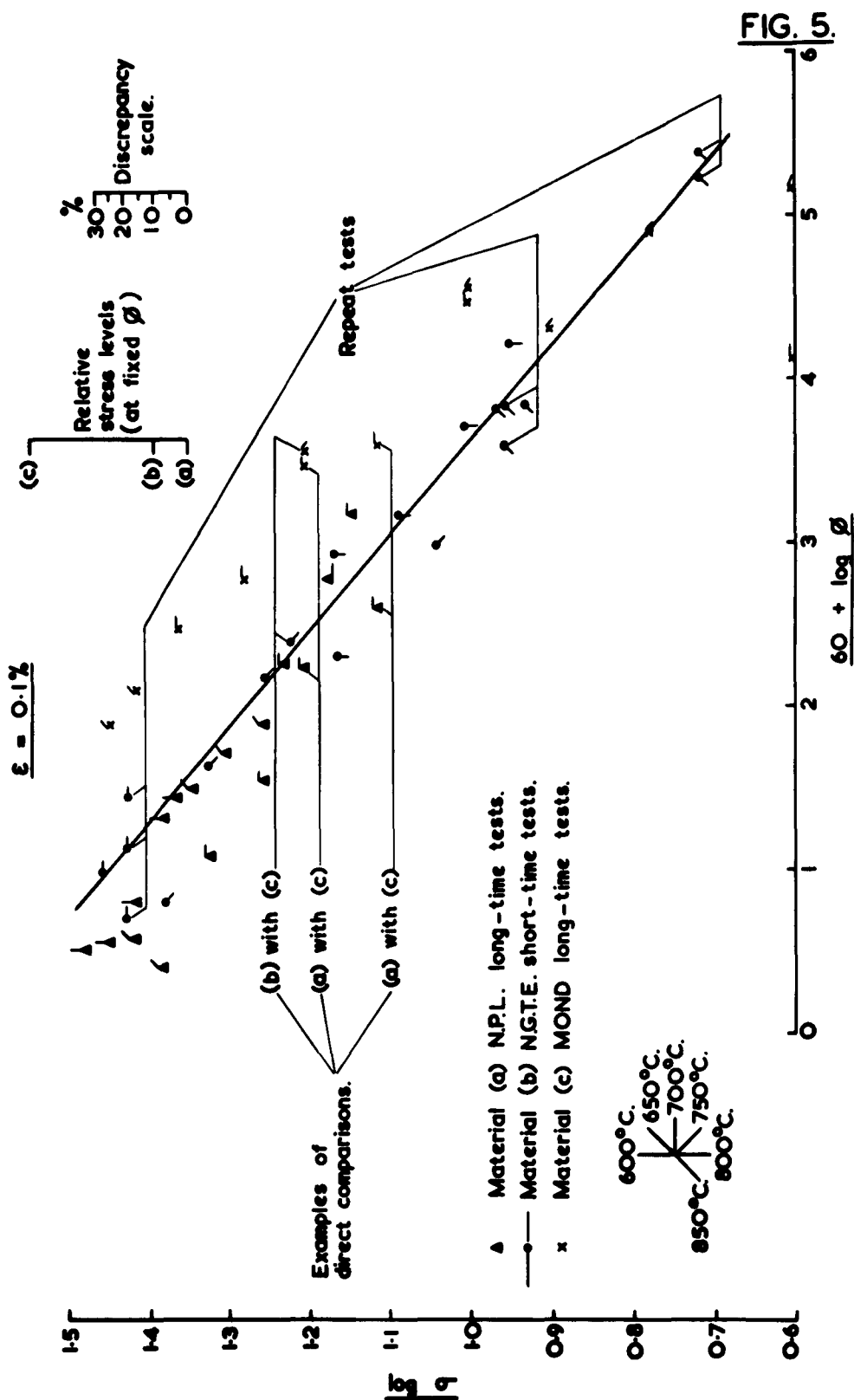FIG.6

LOG σ VERSUS LOG ∅ FOR t³ TERM.

FIG. 7
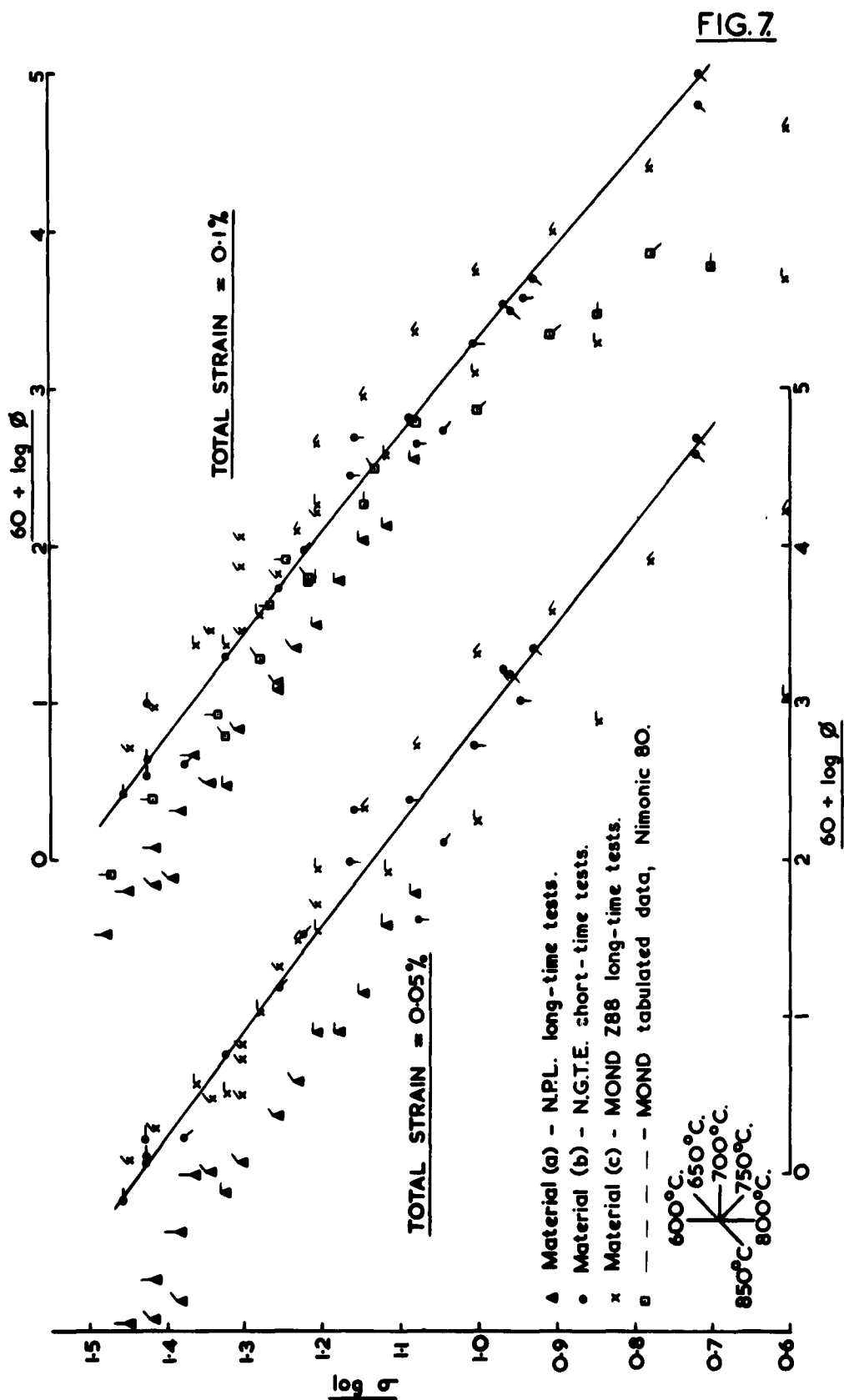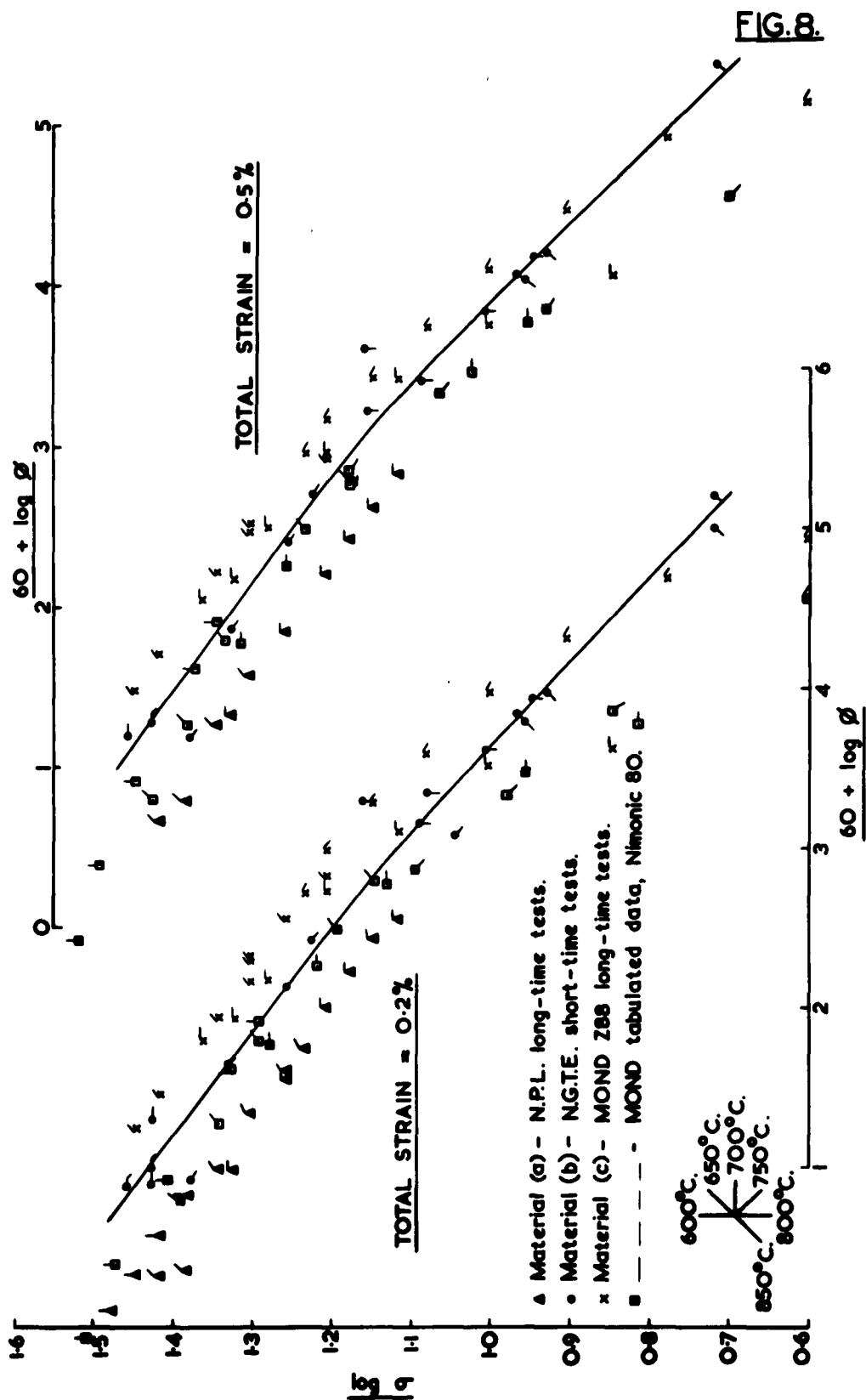
SK 6591

TOTAL STRAIN = 0·1%

TOTAL STRAIN = 0·05%

60 + log ∅

60 + log ∅

log σ

▲ Material (a) – N.P.L. long-time tests.
● Material (b) – N.G.T.E. short-time tests.
✕ Material (c) – MOND Z88 long-time tests.
▱ ——— MOND tabulated data, Nimonic 80.

600°C. 650°C. 700°C. 750°C.
850°C. 800°C.

LOG σ VERSUS LOG ∅ FOR FIXED TOTAL STRAIN.

FIG. 8.

LOG σ VERSUS LOG ∅ FOR FIXED TOTAL STRAIN.

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    Availability Open Document, Open Description, Normal Closure before FOI Act: 30 years
    Former reference (Department) R137
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